

CONTENTS

	Page
EXECUTIVE SUMMARY.....	v
ACRONYMS AND ABBREVIATIONS	ix
GLOSSARY.....	xiii
1. INTRODUCTION.....	1
1.1 OBJECTIVES	5
1.2 PMR SCOPE AND BACKGROUND INFORMATION	6
1.2.1 Scope of UZ Flow and Transport PMR	6
1.2.2 Principal Factors and Other Factors Considered.....	7
1.2.3 Features, Events, and Processes (FEPs)	9
1.2.4 Summary of Current Understanding of Flow and Transport at Yucca Mountain	12
1.3 QA STATUS OF DATA AND SOFTWARE.....	18
1.3.1 Acquired and Developed Data	19
1.3.2 Software	19
1.3.2.1 TOUGH2	19
1.3.2.2 ITOUGH2.....	19
1.3.2.3 TOUGHREACT	20
1.3.2.4 Transport Codes	20
1.4 RELATIONSHIP TO OTHER PROCESS MODEL REPORTS AND KEY PROJECT DOCUMENTS	23
2. EVOLUTION OF THE UZ SITE CHARACTERIZATION PROGRAM – DATA COLLECTION AND MODEL DEVELOPMENT SUPPORTING THE UZ PMR	25
2.1 UZ CHARACTERIZATION PROGRAM AT YUCCA MOUNTAIN	25
2.1.1 Development and Documentation of the Site Characterization Program	26
2.1.2 Chronology of Drilling/Excavation, Testing, and Modeling	26
2.1.3 Stimulating Issues for the UZ.....	28
2.1.4 Yucca Mountain Boreholes and ESF Drifts	29
2.2 DATA COLLECTION AND <i>IN SITU</i> FIELD TESTING.....	31
2.2.1 Geological Reconnaissance and Data Collection.....	31
2.2.2 Hydrological Testing and Data Collection.....	33
2.2.2.1 Surface-Based Investigations and Hydrological Property Measurements.....	33
2.2.2.2 Underground Testing and Monitoring.....	36
2.2.3 Geochemical Data Collection.....	40
2.2.3.1 Mineral and Solubility Measurements	40
2.2.3.2 Geochemical Measurements	41
2.2.3.3 Isotopic Measurements.....	41
2.2.3.4 UZ Transport Tests.....	42
2.2.4 Thermal Testing	42

CONTENTS (Continued)

	Page
2.2.4.1 Thermal-Hydrological Modeling	42
2.2.4.2 Thermal Characterization and Pre-ESF Testing.....	43
2.2.4.3 Underground Thermal Tests.....	43
2.3 NATURAL ANALOGS AS COLLABORATIVE INFORMATION	45
2.4 EVOLUTION OF UZ AND TSPA MODELS	49
2.5 KEY ISSUES FOR UNSATURATED ZONE FLOW AND TRANSPORT	52
2.5.1 Summary of Key Issues from External Reviewers	52
2.5.1.1 Summary of the TSPA Peer Review Panel	53
2.5.1.2 Summary of the UZ Flow and Transport Model Independent Evaluation Panel.....	58
2.5.1.3 Summary of the Drift-Scale Seepage Peer Review.....	58
2.5.1.4 Summary of the Unsaturated Zone Flow Expert Elicitation.....	59
2.5.1.5 Summary of Nuclear Waste Technical Review Board Issues....	59
2.5.1.6 Summary of Nye County Issues.....	60
2.5.2 Summary of Key Project Issues	60
2.5.2.1 TSPA-VA.....	60
2.5.2.2 Summary of PA Workshop on UZ Flow and Transport	62
2.5.2.3 Summary of the UZ Flow and Transport Model Workshop	63
3. UZ FLOW AND TRANSPORT MODEL AND ABSTRACTIONS	67
3.1 INTRODUCTION.....	67
3.2 GEOLOGICAL CONSIDERATIONS FOR FLOW AND TRANSPORT	69
3.2.1 Overview	69
3.2.2 Major Hydrogeological Units.....	71
3.2.2.1 Tiva Canyon Welded (TCw) Hydrogeological Unit	73
3.2.2.2 Paintbrush Nonwelded (PTn) Hydrogeological Unit.....	74
3.2.2.3 Topopah Spring Welded (TSw) Hydrogeological Unit	74
3.2.2.4 Calico Hills Nonwelded (CHn) Hydrogeological Unit	76
3.2.2.5 Crater Flat Undifferentiated (CFu) Hydrogeological Unit.....	76
3.2.2.6 Water Table Configuration.....	76
3.2.3 Structural Setting.....	77
3.2.4 Mineral Alteration and the Vitric-Zeolitic Boundary.....	78
3.2.5 Summary	80
3.3 PHYSICAL PROCESSES	81
3.3.1 Climate	81
3.3.2 Infiltration.....	81
3.3.3 Fracture and Matrix Flow Component.....	82
3.3.3.1 Flow Through the TCw Unit.....	82
3.3.3.2 Flow Through the PTn Unit	83
3.3.3.3 Flow Through the TSw Unit	83
3.3.3.4 Flow Below the Potential Repository.....	84
3.3.4 Fracture-Matrix Interaction	84
3.3.5 Effects of Major Faults.....	86

CONTENTS (Continued)

	Page
3.3.6 Transient Flow.....	87
3.3.7 Flow Focusing	87
3.3.8 Perched Water	88
3.3.9 Seepage into Drifts	88
3.3.10 Gas Flow Processes	89
3.3.11 Radionuclide Transport Processes	89
3.3.12 Effects of Coupled Processes	91
3.3.12.1 TH Processes	91
3.3.12.2 TMe Processes.....	92
3.3.12.3 TC Processes	92
3.3.13 Alternative Conceptual Models.....	92
3.3.14 Summary and Conclusions.....	93
3.4 NUMERICAL MODELS AND GRIDS	95
3.4.1 Numerical Models for UZ Flow and Transport	95
3.4.1.1 Continuum Models.....	95
3.4.1.2 Discrete Fracture-Network Models	96
3.4.1.3 Numerical Models for UZ Flow and Transport at Yucca Mountain	97
3.4.1.4 Some Important Issues for Flow and Transport Modeling	98
3.4.2 Development of Numerical Grids	99
3.4.2.1 Input	100
3.4.2.2 Data Integration and Grid Generation.....	102
3.4.2.3 Output.....	104
3.4.2.4 Grid Refinement Studies	105
3.4.3 Summary	106
3.5 CLIMATE AND INFILTRATION.....	107
3.5.1 Future Climate Analysis.....	108
3.5.1.1 Introduction	108
3.5.1.2 Analysis and Assumptions	109
3.5.1.3 Timing of Climate Change.....	110
3.5.1.4 Nature of Future Climates	111
3.5.1.5 Uncertainties.....	114
3.5.1.6 Alternative Conceptual Models.....	114
3.5.1.7 Corroborative Evidence.....	114
3.5.1.8 Summary and Conclusions.....	115
3.5.2 Infiltration Model	116
3.5.2.1 Introduction	116
3.5.2.2 Analysis and Assumptions	116
3.5.2.3 Hydrological Data Collected at Yucca Mountain	117
3.5.2.4 Conceptual Model for Net Infiltration	118
3.5.2.5 Net Infiltration for the Three Climate Scenarios.....	118
3.5.2.6 Uncertainties.....	121
3.5.2.7 Alternative Conceptual Models.....	122

CONTENTS (Continued)

	Page	
3.5.2.8	Corroborative Evidence.....	122
3.5.2.9	Model Validation.....	123
3.5.2.10	Summary and Conclusions.....	123
3.5.3	Abstraction of Climate and Infiltration	124
3.5.3.1	Climate	124
3.5.3.2	Infiltration.....	124
3.6	UZ PROPERTIES DEVELOPMENT	127
3.6.1	Introduction	127
3.6.2	Issues	129
3.6.3	Analysis of Hydrologic Properties Data.....	130
3.6.3.1	Matrix Property Data.....	130
3.6.3.2	Fracture Property Data	132
3.6.3.3	Fault Property Data	133
3.6.3.4	Thermal Property Data	134
3.6.4	Calibrated Properties Model.....	134
3.6.4.1	1-D Inversions	136
3.6.4.2	2-D Inversions	138
3.6.5	Results and Discussion.....	138
3.6.5.1	Results	138
3.6.5.2	Uncertainty	140
3.6.5.3	Validation	140
3.6.5.4	Alternative Conceptual Models.....	141
3.6.6	Summary and Conclusions.....	142
3.7	FLOW MODEL	145
3.7.1	Introduction	145
3.7.1.1	Objectives.....	145
3.7.1.2	UZ Flow Issues.....	146
3.7.2	Description of the Flow Model	147
3.7.3	UZ Flow Submodels.....	150
3.7.3.1	PTn Flow Studies	150
3.7.3.2	Effects of Major Faults.....	153
3.7.3.3	Investigations of Calico Hills and Perched Water Occurrence	156
3.7.4	Site-Scale Flow Analysis	160
3.7.4.1	Percolation Flux at the Potential Repository Horizon.....	160
3.7.4.2	Repository Percolation Flux Frequency Distribution.....	161
3.7.4.3	Fracture and Matrix Flow Components	162
3.7.4.4	Model Validation and Confidence Building	164
3.7.4.5	Bounds on Percolation and Uncertainties/Limitations.....	166
3.7.4.6	Corroborative Evidence and Natural Analog	167
3.7.4.7	Alternative Conceptual Models.....	167
3.7.5	UZ Flow Abstractions for TSPA-SR	168
3.7.5.1	Abstraction of Flow Fields.....	168

CONTENTS (Continued)

	Page	
3.7.5.2	Abstraction of Water-Table Rise.....	168
3.7.5.3	Abstraction of Perched Water Models	169
3.7.5.4	Abstraction of Groundwater Travel Times	170
3.7.6	Summary and Conclusions.....	170
3.8	AMBIENT GEOCHEMISTRY ANALYSIS AND MODELS	173
3.8.1	Introduction	173
3.8.2	Chloride and $^{36}\text{Cl}/\text{Cl}$ Data and Analysis	174
3.8.3	Evidence for Fast Flow Path and Transport from $^{36}\text{Cl}/\text{Cl}$ and Tritium.....	177
3.8.4	Calcite Simulation Results and Data.....	178
3.8.5	Uncertainties and Limitations	182
3.8.6	Alternative Conceptual Models.....	183
3.8.7	Corroborating Evidence	183
3.8.8	Analogs.....	184
3.8.9	Model Validation.....	184
3.8.10	Summary and Conclusions.....	185
3.9	DRIFT SEEPAGE MODELS	187
3.9.1	Introduction	187
3.9.2	Objectives and General Modeling Approach	190
3.9.3	Key Issues and Corresponding Modeling Assumptions	192
3.9.3.1	Percolation Flux and Channeling Effects.....	192
3.9.3.2	Episodic Flow.....	194
3.9.3.3	Ventilation, Evaporation, and Condensation Effects	194
3.9.3.4	Excavation Effects, Surface Roughness, and Drift Degradation	195
3.9.3.5	Capillary Barrier and Seepage Threshold	197
3.9.4	Seepage Calibration Model	198
3.9.4.1	Objectives and General Approach.....	198
3.9.4.2	Air-Permeability and Liquid-Release-Test Data.....	199
3.9.4.3	Model Assumptions	199
3.9.4.4	Model Development.....	200
3.9.4.5	Model Calibration	200
3.9.4.6	Model Validation.....	202
3.9.4.7	Seepage Threshold Prediction.....	203
3.9.4.8	Summary	203
3.9.5	Seepage Model for PA	203
3.9.5.1	Objectives and General Approach.....	203
3.9.5.2	Model Development.....	204
3.9.5.3	Selection of Parameter Ranges and Case Studies	204
3.9.5.4	Results	205
3.9.6	Abstraction of Seepage into Drifts	206
3.9.6.1	Introduction and Objectives	206
3.9.6.2	Initial Abstraction of Seepage Results	208
3.9.6.3	Adjustments.....	209

CONTENTS (Continued)

	Page
3.9.6.4 Abstraction Results	210
3.9.7 Corroborative Evidence and Analog Studies	212
3.9.7.1 Calcite Depositions in Lithophysal Cavities	212
3.9.7.2 Rainier Mesa	212
3.9.7.3 Altamira.....	213
3.9.7.4 Absence of Seepage into Sealed Drift Segments	213
3.9.8 Alternative Conceptual Models.....	213
3.9.8.1 Discrete Fracture Network Model.....	213
3.9.8.2 Seepage Governed by Ponding Probability.....	214
3.9.9 Summary and Conclusions.....	214
3.10 DRIFT-SCALE THERMAL-HYDROLOGICAL-CHEMICAL PROCESSES AND MODELS	217
3.10.1 Introduction	217
3.10.2 Thermal-Hydrological-Chemical Conceptual Model.....	217
3.10.2.1 TH Processes	217
3.10.2.2 Effects of TH Processes (Boiling, Condensation, and Drainage) on Water and Gas Chemistry and Mineral Evolution	218
3.10.2.3 Effects of Infiltration and Climate Changes on THC Processes	219
3.10.2.4 Hydrologic Property Changes in Fractures and Matrix	220
3.10.3 Modeling Approach, Assumptions, Inputs and Outputs	220
3.10.3.1 Dual-Permeability Model For Reaction-Transport Processes	221
3.10.3.2 Active Fracture Model For Reaction-Transport Processes	221
3.10.3.3 Equilibrium and Kinetic Models for Mineral–Water–Gas Reactions	221
3.10.3.4 Initial and Infiltrating Water and Gas Chemistry and Mineralogy	222
3.10.3.5 Relations for Mineral Reactive Surface Areas	224
3.10.3.6 Relations for Hydrological Property Changes	224
3.10.3.7 Basis for Numerical Code TOUGHREACT V2.2	225
3.10.4 DST THC Model Results and Validation	225
3.10.4.1 Gas-Phase CO ₂ Evolution	226
3.10.4.2 Water Chemistry Evolution.....	227
3.10.4.3 Mineralogical Changes.....	227
3.10.5 THC Seepage Model	227
3.10.5.1 THC Seepage Model Description	227
3.10.5.2 TH Effects	228
3.10.5.3 Gas-Phase CO ₂ Evolution	228
3.10.5.4 Water Chemistry Evolution.....	229
3.10.5.5 Porosity and Permeability Changes and Assessment of Precipitation Cap Formation	230
3.10.6 Uncertainties and Limitations	231

CONTENTS (Continued)

	Page
3.10.7 Alternative Conceptual Models.....	232
3.10.8 Corroborative Evidence.....	232
3.10.9 Analogs.....	232
3.10.10 Model Validation.....	234
3.10.11 Abstraction of Drift-Scale THC Modeling for TSPA-SR	235
3.10.12 Summary and Conclusions.....	236
3.11 UZ TRANSPORT MODEL.....	239
3.11.1 Introduction	239
3.11.1.1 Issues	239
3.11.1.2 Approach	240
3.11.1.3 Assumptions	240
3.11.2 Physical Processes.....	241
3.11.2.1 Flow Processes	241
3.11.2.2 Advection	241
3.11.2.3 Hydrodynamic Dispersion.....	241
3.11.2.4 Sorption	242
3.11.2.5 Matrix Diffusion.....	242
3.11.2.6 Radioactive Decay and Daughter Products.....	243
3.11.2.7 Colloidal Transport	243
3.11.3 Transport Properties	244
3.11.3.1 Sorption Coefficients.....	245
3.11.3.2 Matrix Diffusion Coefficients	247
3.11.3.3 Fracture Aperture and Spacing.....	247
3.11.3.4 Parameters for Colloid-Facilitated Radionuclide Transport	248
3.11.4 Geological Layers below the Potential Repository	248
3.11.5 2-D Radionuclide Transport Simulations.....	250
3.11.5.1 2-D Semi-Analytical Code FRACL	250
3.11.5.2 Simulation Approach.....	250
3.11.5.3 Transport in the Individual Hydrogeologic Unit.....	251
3.11.5.4 Transport Simulations below the Potential Repository	251
3.11.6 3-D Site-Scale Radionuclide Transport.....	252
3.11.6.1 EOS9nT Code	252
3.11.6.2 Transport Simulation of ⁹⁹ Tc	253
3.11.6.3 Transport Simulations of ²³⁷ Np and its Daughter Products....	253
3.11.6.4 Transport Simulations of ²³⁹ Pu and Its Daughters	254
3.11.6.5 Transport-Controlling Features	254
3.11.7 3-D Site-Scale Transport of Pu True Colloids	255
3.11.7.1 Colloidal Forms, Properties, and Filtration Model	255
3.11.7.2 Colloid Transport Simulations	255
3.11.8 Groundwater Travel Times	256
3.11.9 Alternative Models	258
3.11.9.1 Radionuclide Transport Simulations	258
3.11.9.2 Colloidal Transport Simulation.....	258

CONTENTS (Continued)

	Page
3.11.10 Uncertainty and Limitations.....	259
3.11.10.1 Assumptions	259
3.11.10.2 Sorption	259
3.11.10.3 Matrix Diffusion.....	260
3.11.10.4 Radioactive Decay and Daughter Products.....	260
3.11.10.5 Radionuclide Transport Simulations	261
3.11.10.6 Colloidal Transport	261
3.11.11 Model Validation.....	261
3.11.11.1 Alcove Tracer Test.....	261
3.11.11.2 Busted Butte Tracer Test.....	262
3.11.12 Analogs to Radionuclide Transport in the UZ	264
3.11.12.1 Natural Analog Studies at Peña Blanca, Mexico	264
3.11.12.2 Uranium Deposits in Northwestern Nevada/Southeastern Oregon.....	264
3.11.12.3 Akrotiri Archeological Site, Santorini, Greece	264
3.11.13 Abstraction of Transport Model.....	265
3.11.13.1 Introduction	265
3.11.13.2 Assumptions	265
3.11.13.3 Approach	266
3.11.13.4 Results	268
3.11.14 Summary and Conclusions.....	269
3.12 MOUNTAIN-SCALE TH MODEL.....	273
3.12.1 Introduction	273
3.12.2 Modeling Approach.....	274
3.12.2.1 Conceptual Model	275
3.12.2.2 Numerical Grids	275
3.12.2.3 Potential Repository Thermal Load	276
3.12.2.4 Boundary and Initial Conditions	277
3.12.2.5 Input Data and Parameters	277
3.12.3 Results of TH Simulations	278
3.12.3.1 Temperature	279
3.12.3.2 Saturation	281
3.12.3.3 Water Flux.....	282
3.12.4 Model validation	285
3.12.5 Summary and Conclusions.....	286
3.13 OVERVIEW OF UNCERTAINTIES IN UZ FLOW AND TRANSPORT MODELS	289
4. RELATIONSHIP TO NRC ISSUE RESOLUTION STATUS REPORTS.....	293
4.1 SUMMARY OF THE KEY TECHNICAL ISSUES	293
4.2 RELATIONSHIP OF THE UZ FLOW AND TRANSPORT PMR TO THE KTIS	294
4.2.1 Evolution of the Near-Field Environment.....	294

CONTENTS (Continued)

	Page
4.2.1.1 Effects of Coupled THC Processes on Seepage and Flow	294
4.2.1.2 Effects of Coupled THC Processes on Radionuclide Transport	296
4.2.2 Radionuclide Transport	296
4.2.2.1 Radionuclide Transport through Porous Rock	296
4.2.2.2 Radionuclide Transport through Fractured Rock	297
4.2.3 Structural Deformation and Seismicity	298
4.2.3.1 Fracturing and Structural Framework of the Geologic Setting.....	298
4.2.4 Thermal Effects on Flow (TEF)	298
4.2.4.1 Is DOE's Thermal Modeling Approach Sufficient to Predict the Nature and Bounds of TEF in the Near Field?.....	299
4.2.4.2 Does DOE's TSPA Adequately Account for TEF?	299
4.2.5 TSPA and Integration.....	300
4.2.5.1 Model Abstraction.....	300
4.2.5.2 Scenario Analysis.....	301
4.2.5.3 Transparency and Traceability	301
4.2.6 UZ and SZ Flow under Isothermal Conditions	301
4.2.6.1 Future Climates and Hydrological Effects on Climate Change: What Is the Likely Range of Future Climates at Yucca Mountain and What Are the Likely Hydrological Effects of Climate Change?	302
4.2.6.2 Present-Day Shallow Infiltration: What Is the Estimated Amount and Spatial Distribution of Present-Day Shallow Infiltration?.....	302
4.2.6.3 Deep Percolation: What Is the Estimated Amount and Spatial Distribution of Percolation through the Proposed Repository Horizon (Present Day and through the Period of Repository Performance)?	302
4.2.6.4 Matrix Diffusion: To what Degree Does Matrix Diffusion Occur in the UZ and SZ?	303
4.3 NRC ACCEPTANCE CRITERIA	303
 5. SUMMARY AND CONCLUSIONS.....	327
5.1 SUMMARY OF THE UZ FLOW AND TRANSPORT PMR	327
5.2 SUMMARY OF MODELS AND ABSTRACTIONS FOR TSPA-SR	330
5.2.1 UZ Flow	331
5.2.2 Drift Seepage.....	332
5.2.3 Drift-Scale THC	333
5.2.4 UZ Transport.....	334
5.2.5 Treatment of Uncertainties.....	335

CONTENTS (Continued)

	Page
6. REFERENCES AND INPUTS	337
6.1 CITED DOCUMENTS	337
6.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES	365
6.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER.....	365
7. ATTACHMENTS	367
ATTACHMENT I – UZ DATA AND ASSOCIATED DATA TRACKING NUMBERS (DTNS)	
ATTACHMENT II – LIST OF DTNS FOR FIGURES AND TABLES	
ATTACHMENT III – FIGURES	